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Study on the reduction of current for a high field superconducting magnet by using a superconducting transformer

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Generally speaking, a high field superconducting magnet like a dipole magnet needs a large excitation current, and its equipment for current excitation becomes very large and complicated for operation. So the authors have developed a magnetic system composed of a superconducting magnet and a superconducting transformer basically used for the reduction of the excitation current[1]. In this study, a fundamental test of the magnet system has been conducted to examine the working principle, and the effectiveness of this system was verified together with the possible reduction in excitation current for the high field superconducting magnet.

Keywords: superconducting magnet; superconducting transformer; excitation current; magnet system

The research and development of superconducting magnets are expected to move more and more toward higher magnetic fields, but there is a tendency to increase excitation currents for such superconducting magnets from the design point of view. This means that a high field superconducting magnet needs a larger-sized power supply. So we have developed a small test apparatus to conduct simulation tests of a superconducting magnet system capable of generating a high magnetic field with one to several tenths of the current of a high field magnet. This system consists of a high field superconducting magnet, power supply and superconducting transformer with the latter installed between the first two. Similar systems have also developed for measurements of critical current for superconducting cables[2,3], but the purpose of our system is to increase the current of a superconducting magnet and this approach has been tried for the first time. The working principle of this magnet system has been verified by the fundamental test described here.

Magnet system

Basic circuit

Figure 1 shows the basic circuit of the magnet system. This system has a superconducting transformer between the high field superconducting magnet (load coil, L_c) and the power supply.
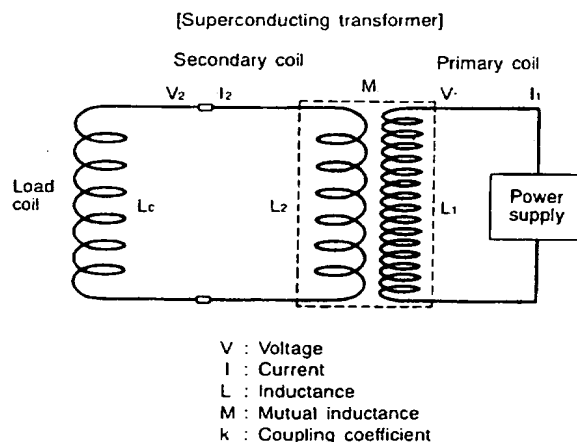

Figure 1 Basic circuit of magnet system

V : Voltage
I : Current
L : Inductance
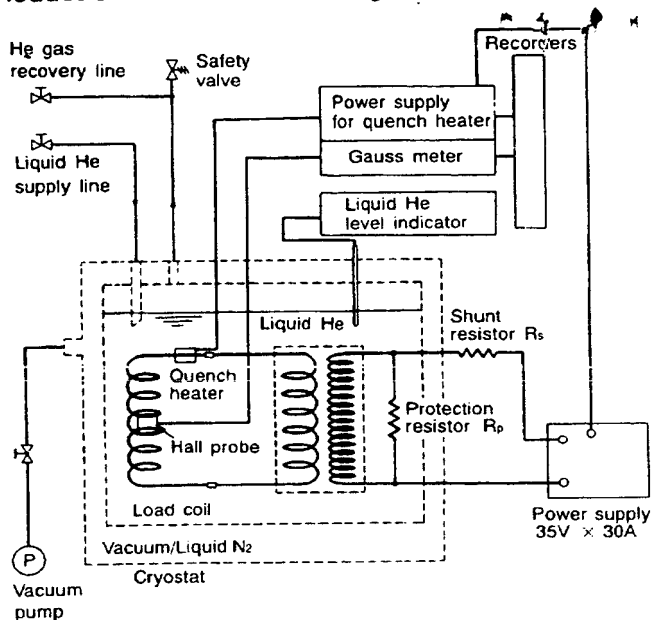M : Mutual inductance
k : Coupling coefficient

Figure 2 Schematic diagram of test apparatus

Calculation of performance

The following equations apply to the case where L_c is connected to the superconducting transformer, on condition that L_1 and L_2 are so positioned as not to be affected by L_c in terms of mutual inductance.

$$V_1 = L_1(dI_1/dt) - M(dI_2/dt) \tag{1}$$

$$V_2 = M(dI_1/dt) - L_2(dI_2/dt) = L_c(dI_2/dt) \tag{2}$$

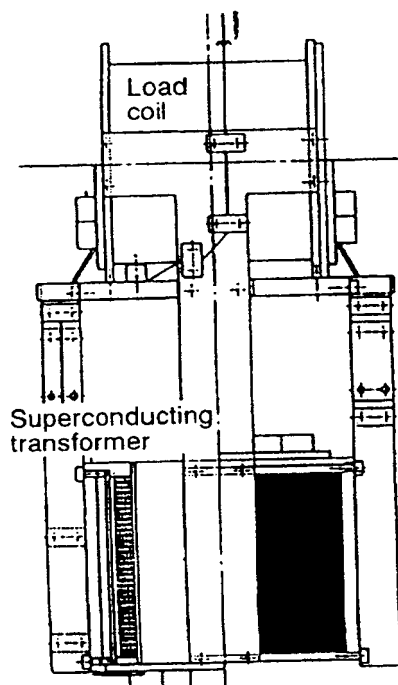The mutual inductance M between L_1 and L_2 can be expressed with the coupling coefficient k.

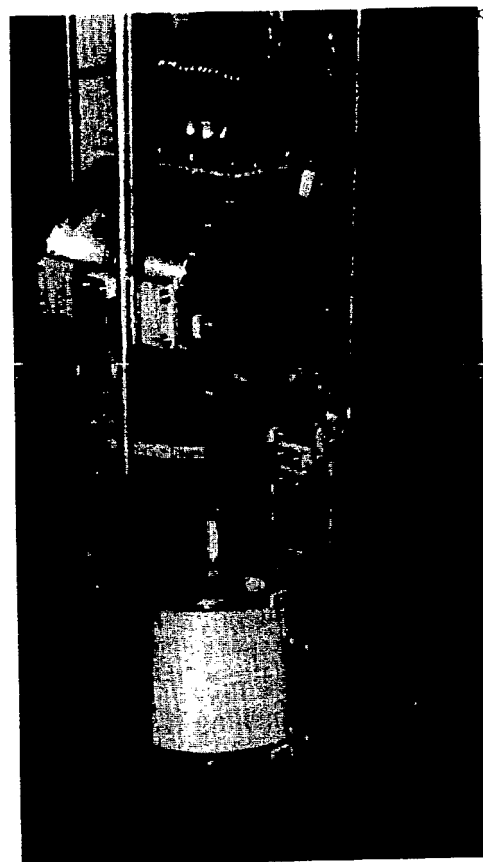**Figure 3** Cross-section of superconducting transformer and load coil

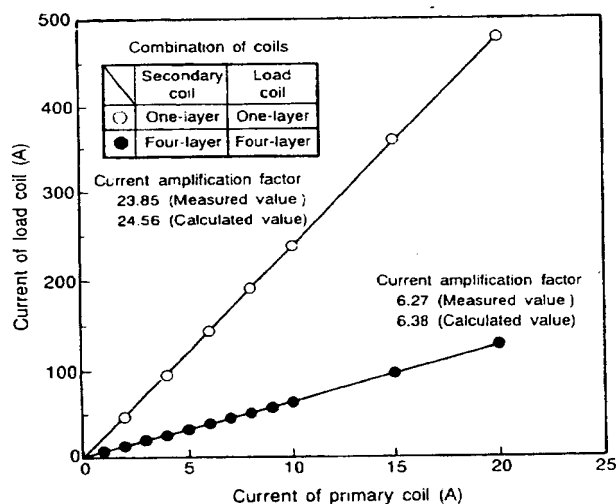**Figure 4** Superconducting transformer and load coil

Figure 5 Current amplification factor

$$M = k(L_1 L_2)^{1/2}$$

The turns ratio n is defined by

$$n = (L_1/L_2)^{1/2} \tag{3}$$

$$M = kL_1/n = nkL_2 \tag{4}$$

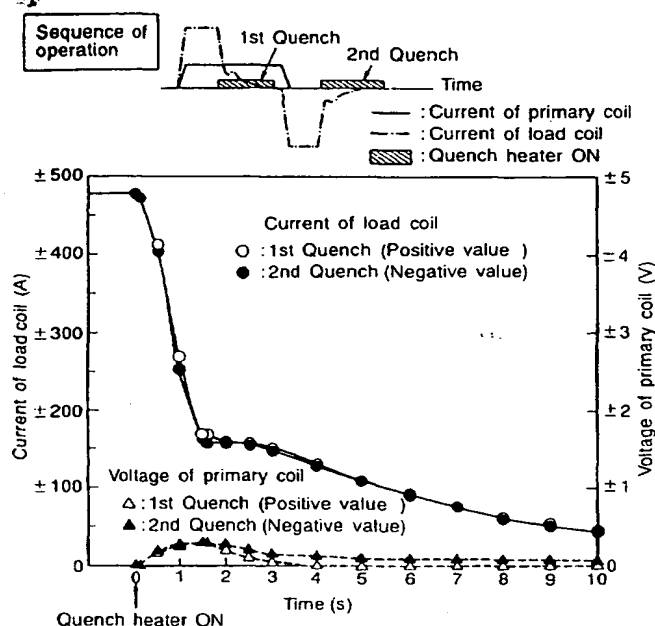Therefore, the current amplification factor m can be expressed from Equation (4) as

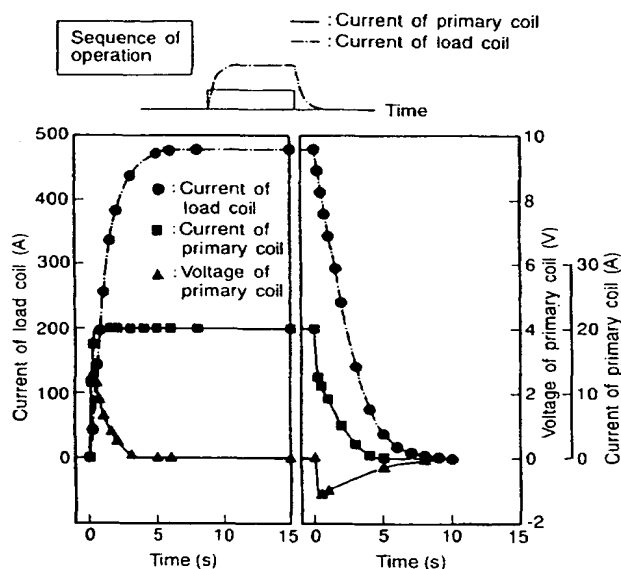**Figure 6** Current attenuation characteristics of load coil by quench heater

Figure 8 Current attenuation characteristics of load coil in persistent mode

Figure 7 Step response characteristics of load coil by power supply

$$m = I_2/I_1 = M/(L_c + L_2) = (kL_1/n)/(L_c + L_2)$$

$$= nkL_2/(L_c + L_2) \tag{5}$$

Substituting Equation (5) into (3), we obtain

$$L_1 = m^2(L_c + L_2)^2/(k^2L_2) \tag{6}$$

$$dL_1/dL_2 = (m^2/k^2)(L_2^2 - L_c^2)/L_2^2 \tag{7}$$

Therefore, when we have $L_2 = L_c$ we can minimize L_1 as below

$$L_1 = 4m^2L_2/k^2 \tag{8}$$

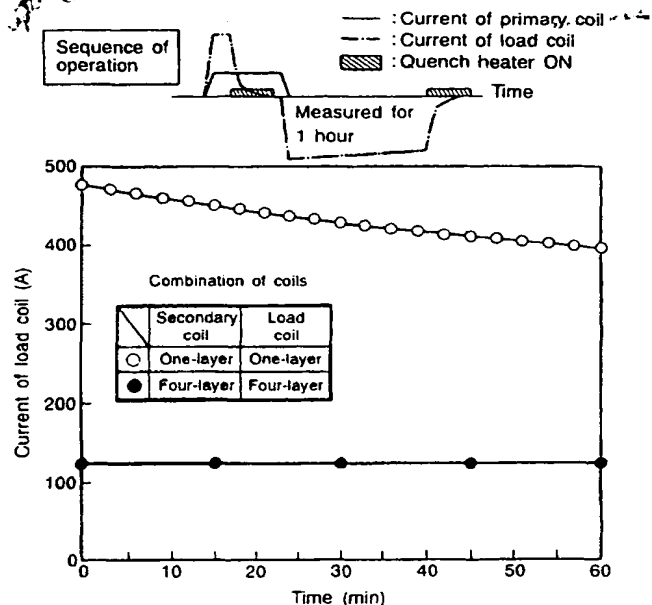i.e. when L_2 is equal to L_c, we obtain the optimum solution,

which leads to setting up a design basis for the superconducting transformer. Then:

1 the time to excite this magnet system at the same excitation voltage can be minimized;
2 the weight and size of the superconducting transformer can also be reduced to a minimum.

In the optimum design of the equal inductance of the load coil and the secondary coil, the total flux generated in the load coil is the same as that in the superconducting transformer. Therefore, in the practical design, the superconducting transformer may be larger than the load coil or high field magnet because the larger superconducting transformer generates the lower magnetic field and is easy to design.

Fundamental test

Test apparatus

Figure 2 shows the schematic diagram of the test apparatus. The secondary current was measured with a Hall probe set at the centre of the load coil. The relationship between the magnetic field and the load current was calibrated with a small current at room temperature before testing at 4.2 K.

Table 1 shows the design specification of the superconducting transformer and the load coil. The load coil is composed of two superconducting coils. One is a four-layer winding coil, and the other is a one-layer winding coil. Each coil is used separately during test. The secondary coil of the superconducting transformer has the same specification as the load coil. Depending on the purpose of the test, the connection between the superconducting transformer and load coil was changed to test two combinations: a 'one-layer to one-layer' combination and a 'four-layer to four-layer' combination. *Figures 3* and *4* show the cross-section of the superconducting transformer and the load coil and photographs of them before cooling to 4.2 K, respectively. Coils are wound around the bobbin made of a non-

Table 1 Design specification of superconducting transformer and load coil

	Superconducting primary coil	Superconducting secondary coil	Load coil	Superconducting secondary coil	Load coil
		Four-layer		One-layer	
Superconducting wire (NbTi)	+0.52	$1.6^H \times 2.8^W$ (stranded 7 wires)			
Inner diameter (mm)	114.4	90.0	90.0	102.9	102.9
Outer diameter (mm)	123.4	102.8	102.8	106.1	106.1
Height (mm)			97.0		
Inductance (mH)	298	1.16	1.12	0.080	0.080
Number of turns	1794	137	135	33	33
Mutual inductance (mH)		14.3	—	3.9	—
Coupling coefficient		0.769	—	0.805	—

magnetic material like stainless steel and the magnetic mutual influence between the load coil and superconducting transformer is prevented by arranging them orthogonally.

Results of fundamental test

1 The current amplification factor between the primary and secondary currents is shown in *Figure 5*. It closely agrees with the designed value.

2 The current attenuation characteristics of the load coil by the quench heater are shown in *Figure 6*. The first quick-released energy was absorbed at the protection resistor, and subsequently quench-back occurred on the secondary side.

3 The step response characteristics of the load coil by the power supply are shown in *Figure 7*.

4 The current attentuation characteristics of the load coil in persistent mode of this test apparatus are shown in *Figure 8*. These were measured for 1 h. In the four-layer coil combination, the attenuation of the current could not be measured at all. But for the one-layer combination, it was possible to measure the attenuation of the current. Because, in that case, the inductance of the coil was as small as 8×10^{-5} mH and the current was raised to four times the four-layer combination case, the effect of the resistance at the connecting point of the load coil and secondary coil of the superconducting transformer became apparent. The value of this resistance at the connection point was estimated to be about 8×10^{-9} Ω.

Conclusions

We have developed a small test apparatus to conduct simulation tests on a superconducting magnet system capable of generating a high magnetic field with one to several tenths of the current of a high field magnet. This system consists of a high field superconducting magnet, power supply and superconducting transformer. In this study, a fundamental test of the magnetic system has been conducted to examine the working principle and we verified the effectiveness of this system and the possible reduction of the excitation current for a high field superconducting magnet. But it is necessary to do further experiments using bigger superconducting transformers in order to be fully confident.

References

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